νMSM—Predictions for Neutrinoless Double Beta Decay

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We give the prediction on the effective Majorana mass for neutrinoless double β decay in a simple extension of the Standard Model (νMSM). The model adds three right-handed neutrinos with masses smaller than the electroweak scale, and explains dark matter of the Universe. This leads to constraints 1.3 meV $< m_{\beta\beta}^{NH} <$ 3.4 meV in normal neutrino mass hierarchy and 13 meV $< m_{\beta\beta}^{IH} <$ 50 meV in inverted hierarchy.

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I. INTRODUCTION

Currently most laboratory experiments are described up to a very good precision by the Standard Model of particle interactions. However, recent developments show that effects beyond the Standard Model surely exist. The anomaly in atmospheric neutrinos is now understood by $\nu_\mu \to \nu_\tau$ oscillation [1, 2], while the solar neutrino puzzle is solved by the oscillation $\nu_e \to \nu_{\mu,\tau}$ [3, 4] incorporating the MSW LMA solution [5, 6, 7, 8]. Current data are consistent with flavor oscillations between three active neutrinos[1] with parameters given in table I. The definition of mixing angles is usual

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\\ -s_{12}c_{23}-c_{12}s_{23}s_{13}\mathrm{e}^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}\mathrm{e}^{i\delta} & s_{23}c_{13}\mathrm{e}^{i\delta}\\ s_{12}s_{23}-c_{12}c_{23}s_{13}\mathrm{e}^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}\mathrm{e}^{i\delta} & c_{23}c_{13}\mathrm{e}^{i\delta}\end{pmatrix} \times \begin{pmatrix}\mathrm{e}^{i\alpha_1/2}\ \nu_1\\ \mathrm{e}^{i\alpha_2/2}\ \nu_2\\ \nu_3\end{pmatrix}\ , \quad (1)$$

where $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$, δ is the usual CP-violating phase and α_1, α_2 are Majorana phases. The three neutrino masses m_i should be added to the parameter set that describes

TABLE I: Neutrino oscillation parameters (2004 status)

Parameter	Value $\pm1\sigma$	Comment
Δm_{21}^2	$7.9^{+0.6}_{-0.5}\times10^{-5}$ eV^2	Solar ν [3, 4]
$\tan^2\theta_{12}$	$0.40^{+0.10}_{-0.07}$	For $\theta_{13}=0$ [3, 4]
$\lvert\Delta m_{32}^2\rvert$	$2.0^{+0.6}_{-0.4}\times10^{-3}$ eV^2	Atmospheric ν [1]
$\sin^2 2\theta_{23}$	>0.95	For $\theta_{13}=0$ [1]
$\sin^2\theta_{13}$	<0.016	[10]

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[1] We do not include the LSND anomaly [9] in present analysis.

the matrix (1), representing therefore nine unknown parameters altogether.

Another strong indication that the Standard Model is not complete comes from cosmology. Recently, various cosmological observations have revealed that the universe is almost spatially flat and mainly composed of dark energy ($\Omega_\Lambda = 0.73 \pm 0.04$), dark matter ($\Omega_{\rm dm} = 0.22 \pm 0.04$) and baryons ($\Omega_b = 0.044 \pm 0.004$) [11].

A promising way of extending the Minimal Standard Model leading to explanation of these facts was proposed in [12]. The idea is to add 3 right-handed neutrinos to the model with the most general gauge-invariant and renormalizable Lagrangian. One then requires that active neutrinos satisfy the known oscillation data, and the (Warm) Dark Matter [13, 14, 15, 16, 17, 18] is given by the right-handed (sterile) neutrinos (one could also try to add only 2 right-handed neutrinos, what is enough to explain oscillation data, but it turns out to be inconsistent with sterile neutrino being Dark Matter). These surprisingly leads to a stringent constraint on the active neutrino masses—the lightest neutrino should have the mass less than about 10^{-5} eV.

Baryon number asymmetry of the Universe can also be explained in νMSM, see Ref. [19]. More constraints on the parameters of the sterile neutrinos appear from that consideration, but no additional restrictions on active neutrino parameters, that are relevant for the current discussion are introduced.

We are going to analyze the effective Majorana mass for neutrinoless double beta decay emerging in this model. Section II revives the main points of νMSM relevant for our discussion, and section III provides the estimate of the effective Majorana mass for neutrinoless double β decay in the model.

II. THE νMSM MODEL

Lagrangian of νMSM, introduced in [12] adds 3 right handed neutrinos to the Standard Model, which are SU(2)×U(1) singlets and have the most general gauge-invariant and renormalizable interactions:

$$\delta\mathcal{L} = \overline{N_I} i\partial_\mu \gamma^\mu N_I - f^\nu_{I\alpha}\,\Phi \overline{N_I} L_\alpha - \frac{M_I}{2}\,\overline{N^c_I} N_I + h.c.\,,$$

where Φ and L_α ($\alpha = e, \mu, \tau$) are the Higgs and lepton doublets, respectively, and both Dirac ($M^D = f^\nu \langle\Phi\rangle$) and Majorana ($M_I$) masses for neutrinos are introduced. We have taken a basis in which mass matrices of charged leptons and right-handed neutrinos are real and diagonal. In [12] this model was called "the ν *Minimal Standard Model* (the νMSM)".

Let us first discuss neutrino masses and mixing in the νMSM. We will restrict ourselves to the region in which the Majorana neutrino masses are larger than the Dirac masses, so that the seesaw mechanism [20] can be applied. Note that this does not reduce generality since the latter situation automatically appears when we require the sterile neutrinos to play a role of dark matter, as we shall see. Then, right-handed neutrinos N_I become approximately the mass eigenstates with $M_1 \le M_2 \le M_3$, while other eigenstates can be found by diagonalizing the mass matrix:

$$M^\nu = \left(M^D\right)^T\ M_I^{-1}\ M^D\,.$$

which we call the seesaw matrix. The mass eigenstates ν_i ($i = 1, 2, 3$) are found from

$$U^T M^\nu U = M^\nu_{\rm diag} = {\rm diag}(m_1, m_2, m_3)\,,$$

and the mixing in the charged current is expressed by $\nu_\alpha = U_{\alpha i}\,\nu_i + \Theta_{\alpha I}\,N_I^c$ where $\Theta_{\alpha I} = (M^D)^\dagger_{\alpha I} M_I^{-1} \ll 1$ under our assumption. This is the reason why right-handed neutrinos N_I are often called "sterile" while ν_i "active".

For three sterile neutrinos added to the SM all active neutrinos acquire masses, and the smallest mass can be in the range $0 \le m_{\rm min} \lesssim \mathcal{O}(0.1)$ eV [21]. In particular, the degenerate mass spectra of active neutrinos are possible when $m_{\rm min}^2 \gtrsim \Delta m_{\rm atm}^2$. Note also that there are two possible hierarchies in the masses of active neutrinos, i.e. "normal" hierarchy $\Delta m_{32}^2 > 0$ leading to $m_1 < m_2 < m_3$, and "inverted" hierarchy $\Delta m_{32}^2 < 0$ with $m_3 < m_1 < m_2$. Note, that here ν_1 is the mass state maximally mixed with the electron flavor neutrino and ν_3 is the mass state maximally mixed with τ neutrino (this is different from the convention $m_1 < m_2 < m_3$ used in [12]).

When the active-sterile neutrino mixing $|\Theta_{\alpha I}|$ is sufficiently small, the sterile neutrino N_I has never been in thermal equilibrium and is produced in non-equilibrium reactions. The production processes include various particle decays and conversions of active into sterile neutrinos. Requirement that enough of Dark Matter neutrino is produced leads to the following constraint on the Dirac mass term in the Lagrangian (see Ref. [12])

$$\sum_I \sum_{\alpha=e,\mu,\tau} \left| M^D_{I\alpha} \right|^2 = m_0^2 \,, \tag{2}$$

where $m_0 = \mathcal{O}(0.1)$ eV and the summation over I is only over sterile neutrinos being Warm Dark Matter. Notice that this constraint on dark-matter sterile neutrinos is independent of their masses, at least for M_I in the range discussed below.

The sterile neutrino, being warm dark matter, further receives constraints from various cosmological observations and the possible mass range is very restricted as

$$2\ \text{keV} \lesssim M_I \lesssim 5\ \text{keV} \,,$$

where the lower bound comes from the cosmic microwave background and the matter power spectrum inferred from Lyman-α forest data [22], while the upper bound is given by the radiative decays of sterile neutrinos in dark matter halos limited by X-ray observations [23].

The constraint (2) together with the neutrino oscillation data leads to the following conclusion. At least 3 right-handed neutrinos are required. In case of only 3 sterile neutrinos only one of them can play the role of WDM (let it be M_1, for definiteness), and the mass of the lightest active neutrino $m_{\rm min}$ should be less than about 10^{-5} eV (see Ref. [12] for details). If there are more than three sterile neutrinos no constraint is present.

In the work [19] baryon asymmetry of the Universe was also explained in the framework of νMSM. Additional constraints from requirement of correct baryon asymmetry arise on the parameters of the sterile neutrinos in νMSM, but no additional constraints appear on the parameters of the active neutrinos relevant for our discussion here.

III. NEUTRINOLESS DOUBLE BETA DECAY EFFECTIVE MASS

The constraints described in the previous section allow to determine the effective mass for neutrinoless double beta decay. This mass is related to the mass eigenvalues and mixings by

$$m_{\beta\beta} = \left| \sum_i m_i U_{ei}^2 + M_1 \Theta_{e1}^2 \right| \,, \tag{3}$$

where the first term corresponds to the standard three neutrino contribution, and the second one is the contribution from the Dark Matter sterile neutrino. The other two sterile neutrinos are considered heavy ($\gtrsim 10$ GeV, see Ref. [19]) and do not contribute to $m_{\beta\beta}$.

First, let us estimate the contribution from the last term. Using definition of Θ_{e1} we get

$$|M_1 \Theta_{e1}^2| = \frac{|M_{1e}^{D\,2}|}{M_1} \; .$$

The dark matter constraint (2) requires $|M_{1e}^{D\,2}| \lesssim (0.1 \text{ eV})^2$. So, the absolute value of the whole contribution is (as far as $M_1 \simeq O(1)$ keV)

$$|M_1 \Theta_{e1}^2| < 10^{-5} \text{ eV} \; .$$

This means that it can be neglected for any reasonable contribution from the first term in (3).

So, standard analysis of the formula (3) can be applied (see eg. [24]). For normal neutrino mass hierarchy we have (as far as m_1 can be neglected)

$$m_{\beta\beta}^{NH} = \left| \sqrt{\Delta m_{21}^2} \sin^2\theta_{12} \cos^2\theta_{13} + \sqrt{|\Delta m_{31}^2|} \sin^2\theta_{13} \mathrm{e}^{-i\alpha_2} \right| \; .$$

For $\theta_{13} = 0$ this leads to $m_{\beta\beta}^{NH} = 2.6 \pm 0.4$ meV. Using 1σ bound on θ_{13} from [10], we get $1.3 \text{ meV} < m_{\beta\beta}^{NH} < 3.4 \text{ meV}$. It is worth noting, however, that for $\tan^2_{13} \geq \sin^2\theta_{12}\sqrt{|\Delta m_{21}^2|/\Delta m_{31}^2} \sim 0.06$ complete cancellation may occur, so at 3σ level $m_{\beta\beta}^{NH}$ can be zero.

In the case of inverted hierarchy, neglecting m_3, one obtains

$$m_{\beta\beta}^{IH} = \sqrt{|\Delta m_{31}^2|} \cos^2\theta_{13} \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \frac{\alpha_2 - \alpha_1}{2}} \; .$$

So, we get $13 \text{ meV} < m_{\beta\beta}^{IH} < 50 \text{ meV}$.

IV. CONCLUSIONS

In the νMSM model the lightest active neutrino has the mass $< 10^{-5}$ eV, and there is a relatively light sterile neutrino with the mass $2 \text{ keV} \lesssim M_1 \lesssim 5$ keV and mixing with active neutrinos of the order of 10^{-4}, which plays a role of the Warm Dark Matter. Though it is quite light, the sterile dark matter neutrino makes a vanishing contribution to effective neutrinoless double β decay Majorana mass $m_{\beta\beta}$ because of its small mixing angle. Thus, predictions for $m_{\beta\beta}$ can be obtained from usual analysis with zero lightest neutrino mass. Specifically, current 1σ limits are

$$1.3 \text{ meV} < m_{\beta\beta}^{NH} < 3.4 \text{ meV}$$

for normal active neutrino mass hierarchy and

$$13 \text{ meV} < m_{\beta\beta}^{IH} < 50 \text{ meV}$$

for inverted hierarchy.

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